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Numerical simulation of the de-bonding phenomenon of FRCM strengthening systems

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Abstract

Aim of the paper is to present a one dimensional simple model for the study of the bond behavior of Fabric Reinforced Cementitious Matrix (FRCM) strengthening systems externally applied to structural substrates. The equilibrium of an infinitesimal portion of the reinforcement and the mortar layers composing the strengthening systems allows to derive the governing equations. An analytical solution is determined solving the system of differential equations. In particular, a nonlinear shear-stress slip law characterized by a brittle post-peak behavior with a residual shear strength in the post peak phase is introduced for either the lower reinforcement-mortar interface (approach 1) or both the lower and the upper interface (approach 2). In the latter approach, a calibration of the shear strength of the upper interface is proposed in order to implicitly account for the effect of the damage of the mortar on the bond behavior. Comparisons with experimental data, available in literature, are presented in order to assess the reliability of the proposed approach.

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Keywords: FRCM; de-bonding; analytical model; interface

1. Introduction

The reinforcement of existing structures has always been a relevant problem both in the technical and scientific civil engineering community. Lately, the study and design of new reinforcement materials is a challenging issue. In

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particular, fabric reinforced cementitious matrix (FRCM) is an emerging strengthening system obtained embedding a grid of the carbon, glass or aramid reinforcement in an inorganic matrix. In general, the matrix is applied as a double layer incorporating the reinforcement. Nowadays, FRCM systems are used in the current practice to reinforce concrete and masonry structures.

Some experimental (D'Ambra et al., 2018; D'Ambrisi and Focacci, 2013; D'Antino et al., 2015; de Felice et al., 2014; Grande et al., 2015; Marcari et al., 2017), theoretical and numerical studies (D'Ambrisi et al., 2012; Grande et al., 2013, 2017; Grande and Milani 2018) on FRCM strengthening systems are available in the recent literature. They testify the efficacy and advantages of FRCM systems together with the need to investigate aspects specifically characterizing the bond behavior of this new family of strengthening systems.

The experimental investigations are mainly shear-lap tests that analyze the local bond behavior of FRCMs (D'Antino et al., 2015). From the experimental evidence different failure mechanisms can occur, such as a cohesive failure of the substrate, de-bonding at the reinforcement/substrate interface, de-bonding at the reinforcement/matrix interface, sliding of the reinforcement, tensile failure of the reinforcement in the un-bonded portion and tensile failure of the reinforcement within the mortar.

The above mechanism occurrence depends on the characteristics of the strengthening system as well as of the support, such as the mechanical properties of the materials, the thickness of the mortar layers and the configuration of the reinforcement. These mechanisms particularly underline the role of additional phenomena to be necessarily considered for the study and the development of theoretical models/design formulas specific for FRCMs.

In this paper a one dimensional simple model, based on the one presented in Grande et al. (2017) and Grande et al. (2018), is proposed for the study of the bond behavior of FRCM strengthening systems externally applied to masonry substrates. The model is mainly characterized by the derivation of the explicit solution of a system of differential equations obtained by considering the equilibrium of an infinitesimal portion of the reinforcement and the mortar layers composing the strengthening systems. In order to model the slip between the reinforcement and the upper and lower mortar layers, two approaches are considered. The first approach (denoted in the following approach 1), considers a nonlinear behavior of the lower reinforcement/mortar interface only, by considering a shear stress-slip constitutive law characterized by a linear fragile behavior with a residual strength in the post-peak phase. On the other hand, the approach 2 assumes a nonlinear behavior for both the lower and the upper reinforcement/mortar interface, still considering a shear stress-slip constitutive law characterized by a linear fragile behavior with a residual strength in the post-peak phase. Moreover, in the latter approach, a calibration of the shear strength of the upper interface is proposed in order to implicitly account for the effect of the damage of the mortar on the contribution of this component of the strengthening system.

Both the proposed approaches are validated in the paper by considering experimental results derived from the literature. Moreover, the results are also compared with the ones obtained by the model recently proposed by Grande et al. (2017) and Grande et al. (2018), where, differently from the proposed approaches, the damage of the upper mortar was explicitly introduced in the model by assuming a nonlinear behavior in terms of normal stress-strain for the upper mortar layer. Although this assumption allows to account for the phenomena generally observed, it leads to a computational effort significantly greater than the one characterized the two approaches proposed in this paper.

2. Model and proposed approaches

The model considered in the paper for the numerical study of the bond behavior of FRCM systems externally applied on masonry or concrete supports is based on the work by Grande et al. (2017) and Grande et al. (2018). Making reference to Fig. 1, the analyzed strengthening system, characterized by length L, is made by a cohesive support, a lower mortar layer, a lower interface, a grid for the strengthening, a upper interface and a upper mortar layer. A reference axis x in the direction of the reinforcement system is introduced fixing the origin in correspondence of the unloaded section.

Considering the equilibrium of forces characterizing an infinitesimal portion of the reinforcement and the upper mortar layer (see Fig. 1) the following system of differential equations governing the problem of the bond behavior is obtained:

$$\begin{cases} \dfrac{d\sigma_p}{dx} b_p t_p - \left[\tau^e\left(s^e\right) + \tau^i\left(s^i\right)\right] b_p = 0 \\ \dfrac{d\sigma_c^e}{dx} b_p t_c^e + \tau^e\left(s^e\right) b_p = 0 \end{cases} \tag{1}$$

where .. and σ_c^e are the normal stresses in the reinforcement and in the upper mortar, respectively; t_p and t_c^e are the thicknesses of the reinforcement and the upper mortar, respectively; τ^i and τ^e are the shear stresses at lower and upper interfaces, respectively, both depending on the corresponding slips s^i and s^e; b_p is the width of the reinforcement.

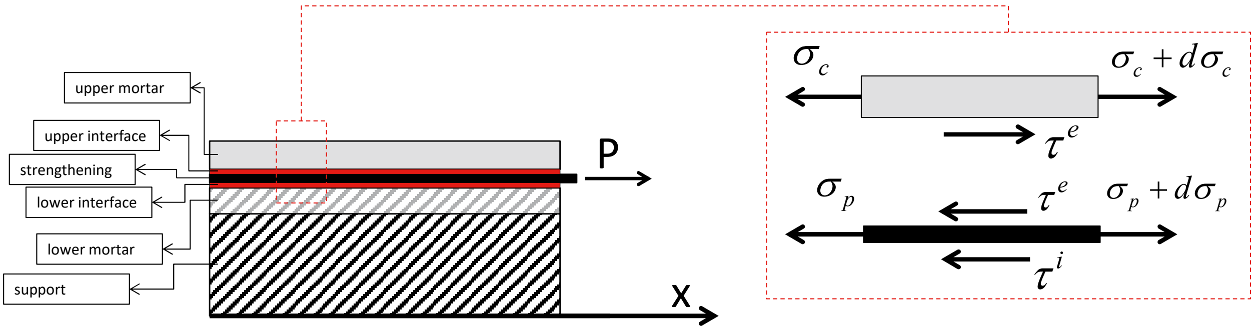


Fig. 1. Schematic of an infinitesimal portion of the strengthening system and the upper mortar component used for performing the equilibrium of the involved forces.

The following hypotheses are introduced:

- the support and the lower mortar layer are assumed to be rigid;
- the (lower and upper) mortar/reinforcement interfaces are modeled as zero-thickness elements with only shear deformability;
- the upper mortar layer and the reinforcement are assumed deformable only axially.

These assumptions allow to write the displacements of both the reinforcement and the upper mortar layer (namely u_p and u_c^e , respectively) as functions of the slip of the lower and upper interfaces:

$$\begin{aligned} u_p &= s^i \\ u_c^e &= s^i - s^e \end{aligned} \tag{2}$$

Then, considering a linear-elastic behavior for both the reinforcement and the mortar:

$$\begin{aligned} \sigma_p &= E_p \frac{du_p}{dx} = E_p \frac{ds^i}{dx} \\ \sigma_c^e &= E_c \frac{du_c^e}{dx} = E_c \left(\frac{ds^i}{dx} - \frac{ds^e}{dx}\right) \end{aligned} \tag{3}$$

Taking into account relations (3), the system of differential equations (1) becomes:

$$\begin{cases} \dfrac{d^2 s^i}{dx^2} - K_1 \left[\tau^e \left(s^e \right) + \tau^i \left(s^i \right) \right] = 0 \\ \left(\dfrac{d^2 s^i}{dx^2} - \dfrac{d^2 s^e}{dx^2} \right) + K_2 \tau^e \left(s^e \right) = 0 \end{cases} \tag{4}$$

where K_1 and K_2 are two constants equal to:

$$K_1 = \frac{1}{E_p t_p}, K_2 = \frac{1}{E_c t_c^e} \tag{5}$$

Starting from the system (4), aim of this paper is to numerically investigate the bond behavior of FRCMs externally applied on masonry substrates by particularly focusing the attention on the shear stresses transfer mechanism at the reinforcement/mortar interface level. For this aim, the explicit solution of the system (4) is derived by introducing different shear stress-slip laws characterizing the behavior of the reinforcement/mortar interface.

2.1. Approach 1: nonlinear behavior of the lower interface

The first approach is based on the assumption of a linear-fragile behavior with a residual shear strength in the post-peak stage only for the lower interface:

$$\begin{cases} \tau^i (s^i) = G^i s^i & s^i \le s_1 \\ \tau^i (s^i) = \tau^i_{res} & \text{otherwise} \end{cases} \tag{6}$$

where τ^i_{res} is the residual value of the shear strength in the post-peak stage, and G^i is the shear stiffness of the lower interface in the pre-peak stage.

On the contrary, a linear elastic behavior is considered for the upper interface $\tau^e (s^e) = G^e s^e$, where G^e is the shear stiffness of the upper interface.

In this case, after the attainment of the slip threshold value at the lower interface, the specimen is divided into two parts: part "1" where the upper mortar and the interfaces are both in the pre-peak stage and part "2" where the upper mortar and the upper interface are both in the pre-peak stage while the lower interface is de-bonded for a length *a*, representing an unknown of the problem. Thus, four differential equations govern the problem.

The first two equations are derived by considering the equilibrium involving an infinitesimal portion of the strengthening system in the part "1":

$$\begin{cases} \dfrac{d^2 s_1^i}{dx^2} - K_3 \left[s_1^e + \alpha \, s_1^i \right] = 0 \\ \left(\dfrac{d^2 s_1^i}{dx^2} - \dfrac{d^2 s_1^e}{dx^2} \right) + K_4 s_1^e = 0 \end{cases} \qquad 0 < x < L - a \tag{7}$$

where: $K_3 = K_1 G^e, K_4 = K_2 G^e,\ \alpha = \dfrac{G^i}{G^e}$.

The other two equations are derived by considering the equilibrium involving an infinitesimal portion of the strengthening system in the part "2":

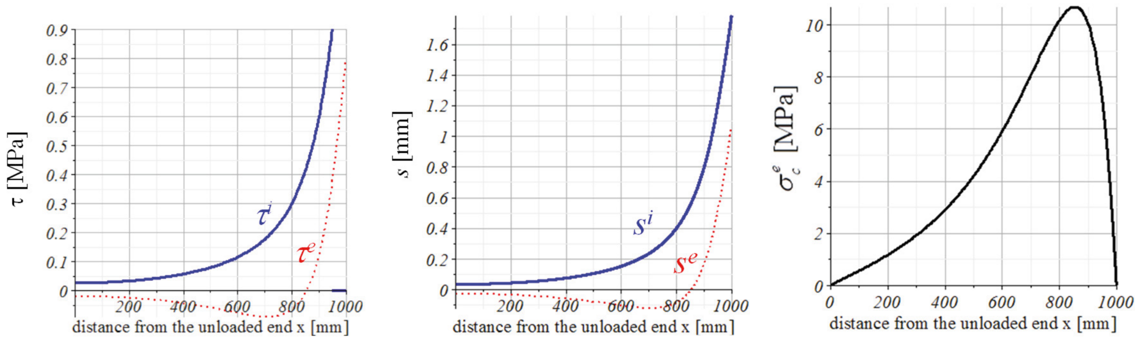
$$\begin{cases} \dfrac{d^2 s_2^i}{dx^2} - K_3\left[s_2^e + \beta\right] = 0 \\ \left(\dfrac{d^2 s_2^i}{dx^2} - \dfrac{d^2 s_2^e}{dx^2}\right) + K_4 s_2^e = 0 \end{cases} \qquad L - a < x < L \tag{8}$$

where $\beta = \dfrac{\tau_{res}^i}{G^e}$.

The system of differential equations (7) and (8) has an analytical solution that depends on eight constants of integration determined by introducing suitable boundary conditions. In particular, the following conditions are indeed enforced:

$$\begin{array}{ll} \sigma_{P1}(0) = 0 & \\ \sigma_{c1}^e(0) = 0 & \sigma_{c2}^e(L) = 0 \\ \sigma_{c1}^e(L-a) = \sigma_{c2}^e(L-a) & \\ \sigma_{p1}^e(L-a) = \sigma_{p2}^e(L-a) & \\ s_1^i(L-a) = s_2^i(L-a) & s_1^e(L-a) = s_2^e(L-a) \\ s_1^i(L-a) = s_1 & \end{array} \tag{9}$$

The solution is graphically reported in Fig. 2 by considering a length value of the part “2” equal to *a*=50 mm, a residual value of shear strength equal to zero and the data reported in Table 1.



a) b) c)

Fig. 2. Approach 1: a) shear stress developing at the interfaces; b) slip of the interfaces; c) normal stresses at the upper mortar layer.

Table 1. Data accounted for numerical analyses.

	symbol [unit]	value
Young’s modulus of the reinforcement	E_p [MPa]	206000
Young’s modulus of the mortar	E_c [MPa]	7000
equivalent thickness of the reinforcement	t_p [mm]	0.054
thickness of the mortar	t_c [mm]	4
width of the reinforcement	b_p [mm]	60
width of the mortar	b_c [mm]	60
bond length	L [mm]	1000

2.2. Approach 2: nonlinear behavior of both the interfaces

The approach 1 does not consider neither the damage of the upper mortar layer nor the damage of the corresponding reinforcement/mortar interface. Differently, as shown in Grande et al. (2018) and Grande and Milani (2018), the damage of the upper mortar generally occurs before the slipping of the interfaces. This particularly influences the shear stress transfer mechanism at the upper interface preventing any further increasing of shear stresses at the upper reinforcement/mortar interface.

This phenomenon is here simple introduced by considering an elastic-fragile behavior also for the upper interface and assuming for this component of the strengthening system a bond strength equal to the shear stress corresponding to the attainment of the tensile strength of the upper mortar layer. In other words, the effect of the damage of the upper mortar is implicitly introduced into the behavior of the upper interface.

On the basis of this assumption, the system of equations governing the problem has to account for the development of three possible zones: part "1": $0<x<L-(a+b)$, where both the interfaces are in the pre-peak stage and normal stresses in the upper mortar are lower than the tensile strength; part "2": $L-(a+b)<x<L-b$, where the upper interface is in the post-peak stage (the length of this zone is equal to a); part "3": $L-b<x<L$, where both the interfaces are in the post-peak stage (the length of this zone is equal to b). In particular, while the equations characterizing the part "1" are the eqns. (7), the equations characterizing the part "2" are:

$$\begin{cases} \dfrac{d^2 s_2^i}{dx^2} - K_5\left[s_2^i + \gamma\right] = 0 \\ \left(\dfrac{d^2 s_2^i}{dx^2} - \dfrac{d^2 s_2^e}{dx^2}\right) + K_2 \tau_{res}^e = 0 \end{cases} \qquad L-(a+b) < x < L-b \tag{10}$$

and the equations characterizing the part 3 are:

$$\begin{cases} \dfrac{d^2 s_3^i}{dx^2} - K_1\left[\tau_{res}^e + \tau_{res}^i\right] = 0 \\ \left(\dfrac{d^2 s_3^i}{dx^2} - \dfrac{d^2 s_3^e}{dx^2}\right) + K_2 \tau_{res}^e = 0 \end{cases} \qquad L-b < x < L \tag{11}$$

where: $\gamma = \dfrac{\tau_{res}^e}{G^i}$, $K_5 = K_1 G^i$, a is the length of the part 2, b is the length of the part 3, τ_{res}^e and τ_{res}^i are the residual shear strength values are of the upper and lower interfaces respectively.

The whole system of differential equations (7), (10) and (11) has an analytical solution that depends on twelve constants of integration determined by introducing suitable boundary conditions similar to the ones introduced for the approach 1. The solution is graphically reported in Fig. 3 by considering a length value of the part "2" equal to a=50 mm, a length of the part "3" equal to b=50 mm, a shear strength of the lower mortar equal to 0.9 MPa, a shear strength of the upper mortar equal to 0.45 MPa, a residual value of shear strength equal to zero for both the interfaces and the data reported in Table 1.

3. Comparison with experimental tests

In order to assess the capability of the proposed model in providing a reliable prediction of the bond behavior of FRCM strengthening systems, some case studies derived from the current literature are considered (D'Antino et al., 2015). The case studies, here considered, consist of single lap shear tests of concrete blocks strengthened by a bidirectional unbalanced PBO fiber net with two mortar layers. In particular, in the present research the specimens are considered characterized by a bond length equal to 450 mm and two different values of the reinforcement width: b_p=60 mm and b_p=80 mm. These tests are of particular relevance since the experimental outcomes showed the damage of the upper mortar layer of tested specimens before the slipping at the interface level.

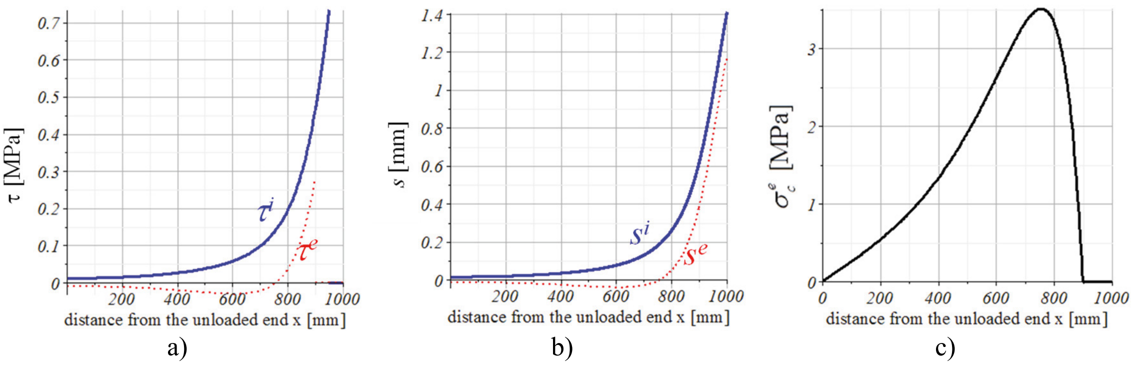


Fig. 3. Approach 2: a) shear stress developing at the interfaces; b) slip of the interfaces; c) normal stresses at the upper mortar layer.

Regarding the application of the approach 1, a shear stress-slip law for the lower interface characterized by a shear strength equal to 0.9 MPa and a slip threshold equal to 1.2 mm is considered (see Grande et al. 2018). On the other hand, for the approach 2 a shear strength value of the upper interface corresponding to the attainment of the tensile strength of the upper mortar layer (f_{ct}=3.5 MPa) is considered. For both the approaches, a null value of the residual shear strength is assumed for both the interfaces.

The obtained results are shown in Fig. 4 in terms of applied load P versus the slip of the lower interface at the loaded section. In the same figure the envelop of the experimental curves (grey region) and the curve carried out in Grande et al. (2018) are also reported.

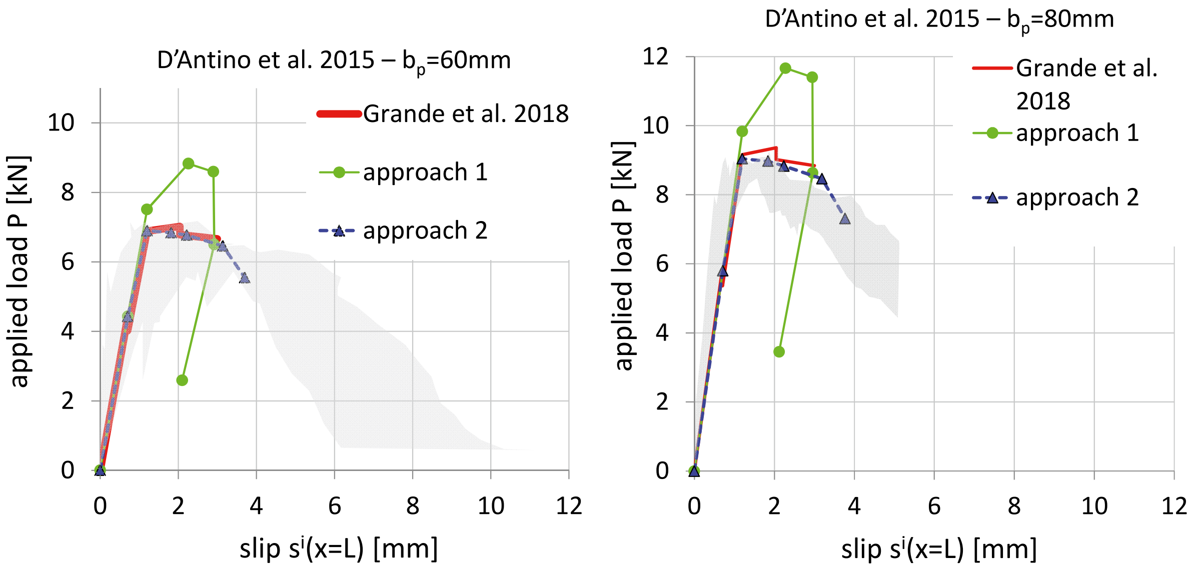


Fig. 4. Comparison with experimental tests.

From the plots clearly emerges the importance of introducing in the model the influence of the damage of mortar on the contribution of the upper interface. Indeed, while the curves deduced from the approach 1 overestimate the experimental peak load, the curves derived by using the approach 2 provide a good approximation of the experimental outcomes.

4. Conclusive remarks

In this paper a one-dimensional simplified model for studying the bond behavior of FRCM strengthening systems externally applied to masonry structures is proposed. The model is based on the study of an infinitesimal portion of the strengthening system composed by the reinforcement and the mortar layers, computing the explicit solution of a system of equilibrium differential equations. Interfaces are introduced between the reinforcement and the upper and lower mortar layers to model the possible slip phenomena. A nonlinear shear-stress slip laws, characterized by a brittle fracture with a residual strength in the post-peak stage, is adopted for the interfaces. Two approaches are developed differing only for the behavior of the upper interface: in the first one the upper interface is characterized by a linear behavior, while, in the second one by the proposed nonlinear response.

The presented model has been applied to two case studies available in the literature.

From the results, approach 2 is able to better describe the experimental results, both in terms of peak load and post peak behavior, with respect to approach 1. In approach 2 the value of the peak shear stress in the upper interface is calibrated in order to take into account the damage occurring in the upper layer of mortar. The results are also compared with the ones obtained by the model proposed by Grande et al. (2017) and Grande et al. (2018).

From a computational point of view, the presented model results simpler than the one proposed by Grande et al. (2017) and Grande et al. (2018), as it doesn't model directly the damage mechanism in the upper layer of mortar but it is able to take it into account by suitable setting the peak shear stress in the constitutive law of the upper interface.

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